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# *Research Department Report*

## **ELECTRIC FIELD STRENGTH METERS FOR THE HF, VHF, AND UHF BANDS**

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**Research Department, Engineering Division  
THE BRITISH BROADCASTING CORPORATION**



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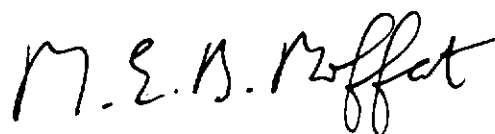
### **Summary**

*The BBC has been deploying two of its own design of RF hazard meters since about 1964. These are used to ensure that levels of RF field can be measured and thus a safe operating régime can be maintained.*

*The scales on the meters have been modified to reflect new guidance from the National Radiological Protection Board, and the meters have therefore needed to be recalibrated.*

*This Report describes the design and calibration methods used including independent certification by the National Physical Laboratory.*

Issued under the Authority of



Head of Research Department

**Research Department, Engineering Division,  
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# ELECTRIC FIELD STRENGTH METERS FOR THE HF, VHF, AND UHF BANDS

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## 1. INTRODUCTION

The BBC has been deploying its own design of RF hazard meters since about 1964. These are used to ensure that levels of RF field can be measured and thus a safe operating regime can be maintained.

Two meters have been designed, one version specifically for the HF band, the other for the VHF and UHF bands. Both meters measure the electric field strength. The HF meter (code-named the ME1/2) covers the frequency range 3 to 30 MHz. The second meter is code-named the ME1/4 and operates over the frequency range 40 to 850 MHz. Compared with many of the meters which are on the market today they are very basic and this is intentional. They are rugged, have only one range of level indication, and are passive devices — thus requiring no power, battery or otherwise. Because of this, errors in indication due to partial or complete battery failure cannot arise, and neither can the operator misread the meter because the wrong range of level indication has been assumed. These are highly desirable features for instruments intended for use by staff when climbing masts or towers where the freedom to handle and operate more sophisticated instruments is very restricted.

Over recent years the levels of RF field which can be tolerated have been under review by various bodies, in particular, the National Radiological Protection Board (NRPB) in the United Kingdom. As a consequence of their revised recommendations<sup>1</sup>, there is a need for the BBC to introduce appropriate 'management levels'\* of field strength which are different from the previous limits. The scales on the BBC meters thus needed modification to reflect these new levels, and the meters needed to be recalibrated.

At the start of the recalibration process, it was found that there was little recorded information about the original calibration process for the meters concerned. Also, measurements at the National Physical Laboratory, backed up by measurements at BBC Research Department, Kingswood Warren, identified that there was a small error in the original calibration of the ME1/4. As the record of the original work was lost it was difficult to identify the cause of this anomaly.

This Report therefore gives a review of all the

work done on the meters. It describes their design and calibration, from the early methods to the current procedures used.

## 2. MEASUREMENT OF RF RADIATION

Before launching into a discussion of the meters themselves it is worthwhile giving a short introduction to the type of measurements that are needed.

The ultimate hazard to people working in high field strengths is that of cooking (denaturation to give it its medical nomenclature). At lower levels of field strength, thermal stress forms the major hazard. Although there is much discussion of other effects, at frequencies above about 10 MHz thermal effects dominate. At the lower end of the frequency range there is an increasing additional risk of shock or involuntary muscular contractions caused by current flow through the body.

Thus ideally the RF hazard meter would provide a reading which identifies the magnitude of the thermal and shock hazards. The thermal hazards are caused by heating up the body and causing a rise in temperature. The shock hazards are caused by currents in the body. Thus the primary safety limits are related to rises in body temperature and body currents. These are difficult to measure directly. Instead, the primary limits are used to derive far-field electric and magnetic field strengths. These derived levels are based on various assumptions about the average person and the environment, in many cases applying a significant margin of safety. They cannot be considered as precise limits. They are called 'reference levels' by the NRPB. Depending on the person and the environment, the reference levels may be exceeded in certain specific conditions without danger. However, before the reference levels are exceeded it is necessary to ensure that the correct procedures are followed to ensure safe working conditions for people needing to enter areas of high RF radiation.

Thus, although it has long been recognised that it is desirable to measure the power flow in an RF field, in practice it is only possible to measure the electric or magnetic field strengths. It is difficult to measure the magnetic field strengths at frequencies in

\* The BBC have for many years used a level of RF field strength as a safety limit. Now, however, the NRPB are recommending the use of lower 'reference levels' for management of exposure to RF radiation. Where fields may exceed these levels, appropriate precautions have to be taken to avoid risk of hazardous exposure, however these levels are stated to be "extremely conservative" and "not to be regarded as limits".

the UHF band and above. This is the reason many meters measure only the electric field strength. The two meters described in this Report are no exception.

The power flow in an electromagnetic field is given by the vector product of the electric and magnetic field components, ( $E$  and  $H$  respectively), of the plane wave, i.e.  $E \times H$ . In the far field, this expression can be simplified because the electric and magnetic fields form an orthogonal set with the direction of propagation. The power density is equal to  $E^2/\eta$  or  $H^2\eta$  where  $\eta$  is  $377 \Omega$ , and is the intrinsic impedance of free space.

In the near field of a radiator, these simplifications no longer hold; in addition to the radiated field, quadrature phase field components exist which contribute to reactive power flow rather than radiated power flow. It is debatable as to whether the high levels of electric or magnetic fields themselves constitute a hazard under these conditions. It is probable that in the presence of a partially conducting body the amplitude of the electric field will be significantly reduced. It can be seen, therefore, that the use of instruments indicating only one field component may lead to some doubt as to the magnitude of the actual power flow and to the extent of the potential hazard when a body is immersed in fields close to the radiator generating them. In general, it may be expected that such field probe measurement will tend to overestimate the potential for hazard when power flow is calculated as if in free space conditions.

Nevertheless, with the interests of safety in mind, it is essential that the working volume near an antenna be explored for high field strength values. These vary rapidly over short distances both because of the near-field effects and because of standing waves set up by metalwork in the area. A careful study of



Fig. 1  
The ME1/4 VHF/UHF  
field strength meter.

the working environment by an experienced operator is necessary.

### 3. VHF/UHF ELECTRIC FIELD STRENGTH METER ME1/4

This meter provides an indication of the electric field strength up to a maximum of 500 V/m, and operates over a frequency range of 40 to 850 MHz. Fig. 1 shows the meter.

The meter comprises a short dipole as the RF probe with a passive detector protected by a Perspex housing attached to the meter case. The circuit diagram is shown in Fig. 2.

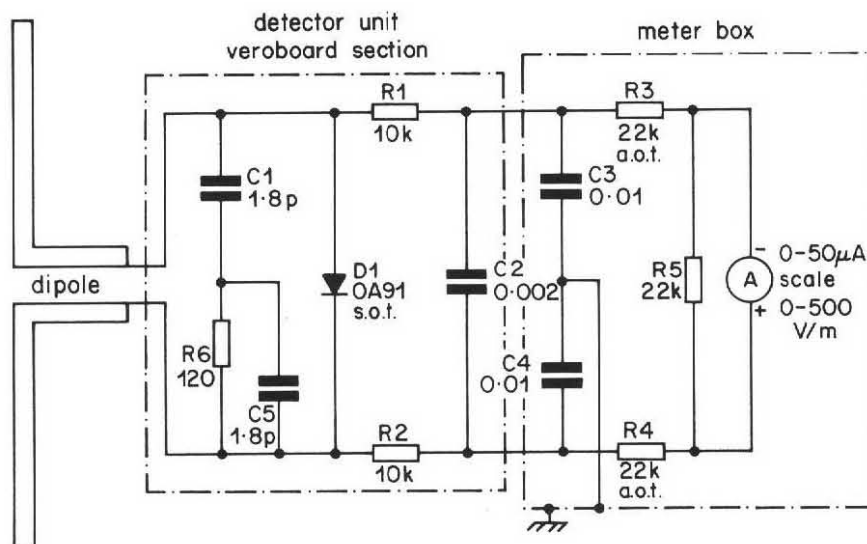


Fig. 2 - Circuit of the ME1/4 meter.



The probe elements are constructed from copper foil strip and have an overall length which is smaller than  $\lambda/2$  at the highest operating frequency for the meter. The elements are sensitive only to the electric field in their plane, and thus need to be turned manually to align with the field to be measured. The elements are terminated with a shunt load (consisting of capacitors  $C_1$  and  $C_5$  and resistor  $R_6$ ), and a shunted diode detector circuit. The frequency response of the meter is substantially flat, because the dipole element impedance is almost a pure negative reactance and, in conjunction with the shunt capacitor, forms a capacitive potentiometer chain and hence, an almost frequency independent circuit. Some control, however, is necessary for adjusting the response at the high frequency end of the band and this is achieved by varying the value of the series resistor ( $R_6$ ).

The meter unit contains the indicating meter and some of the RF decoupling. The unit measures the peak signal level, but is calibrated in r.m.s. levels. The RF time constant has been chosen to give optimum bandwidth and sensitivity.

The sensitivity of the meter is currently set to give a full-scale deflection of 500 V/m. Increasing this value is little problem. All that is necessary is to choose the values of resistors in the meter box to give the desired reading.

If increased sensitivity is wanted then this is limited by the loading of the dipole probe and the non-linearity of the diode detector. The frequency response of the meter may suffer and the scale may become non-linear.

#### 4. HIGH FREQUENCY METER ME1/2

This meter is shown in Fig. 3. Its operating range is intended to cover 3 to 30 MHz, although it is unlikely to be used above 26 MHz within the BBC.

The mechanical arrangement of the meter is similar to that of the ME1/4. The dipole elements are similarly constructed from copper strip, however in this meter they are connected via a strip transmission line to a balun transformer which in turn feeds a series-diode detector circuit. The balun and detector circuit are housed in the meter box. The circuit diagram is shown in Fig. 4.

The meter was originally calibrated with a maximum scale indication of 1000 V/m and at one stage was increased to 1500 V/m, but, in view of changes in the advisory limits for occupational exposure levels, the maximum scale indication has now been reduced to 400 V/m. The meter dimensions are larger than those of the ME1/4 but the increase in size is not a pro-rata increase with operating wavelength.

#### 5. METHODS OF CALIBRATION

The calibration of the meters is a two-stage process. Firstly, a reference meter (referred to as a sub-standard meter) is accurately calibrated. A number of different techniques are used to ensure that it is a valid reference. Then the reference meter is used in a comparison test to calibrate the other meters during the production process.

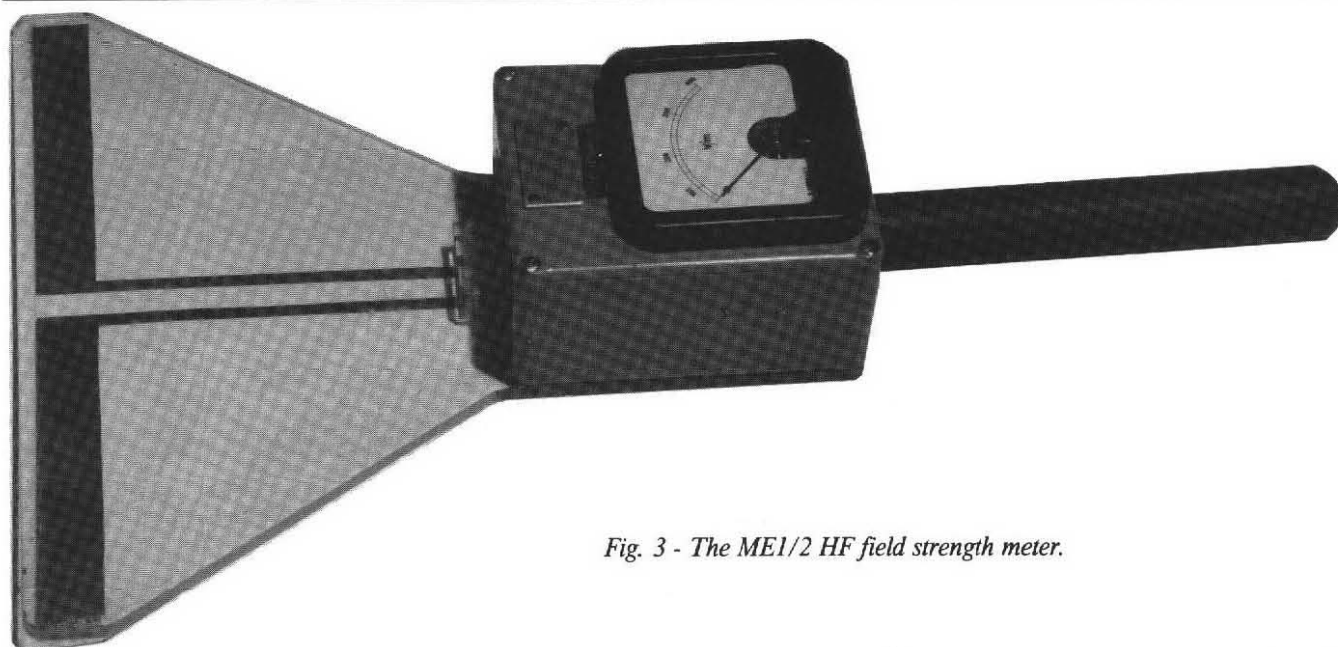


Fig. 3 - The ME1/2 HF field strength meter.

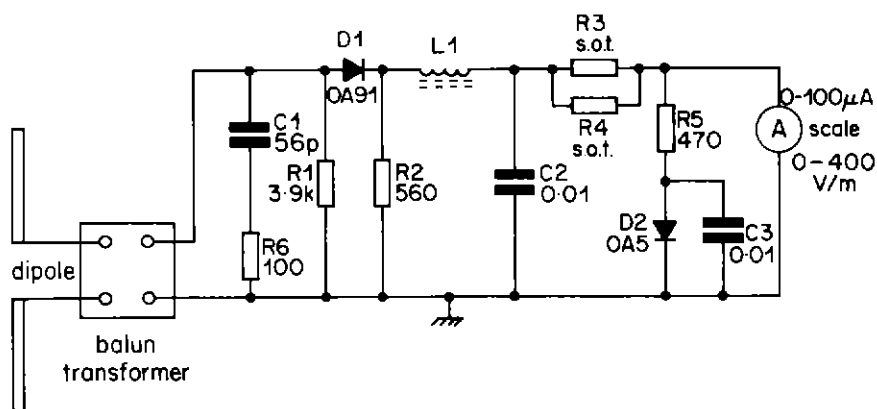


Fig. 4 - Circuit of the ME1/2 meter.

## 5.1 VHF and UHF (ME1/4)

Four different approaches to the calibration have been used. The differences between them are the type of structure used to provide a known field strength. The structures used were:

- transmission lines
- waveguide
- horn aperture
- TEM-mode test cell

### 5.1.1 Transmission line with cylindrical conductors

The meters were originally calibrated (at the lower end of the frequency range) between the conductors of a parallel cylindrical conductor transmission line. This is shown in Fig. 5. The important feature is to ensure that the field between the wires of the transmission line is accurately known.

In the equipment used a  $380 \Omega$  line was effectively short-circuited at its end by a low impedance thermo-couple, the heating element resistance being less than  $1 \Omega$ . The line was fed by a Pawsey stub balun and the matching to the generator for maximum line voltage was by adjustment of the stub length and by the addition of a tuning capacitor. By calibrating the thermo-couple at d.c. the current in the short circuit of the line could be calculated from the measured output from the couple.

From a knowledge of the transmission line geometry and its terminal current, the line voltage and the associated electric field between the conductors can be determined. The advantage of this arrangement is that relatively low-powered RF sources can be used to provide reasonably high field strengths for calibration purposes and the calibration values below the maximum become a function of distance along the line. The field strength between cylindrical conductors is non-linear and it is important that the variation in field strength is taken into account during the calibration process.

At the higher frequencies this method produces unpredictable results because the impedance of the thermo-couple is not known precisely and neither is the length of the short-circuited line known exactly.

### 5.1.2 Balanced parallel plate lines

At the top end of the frequency range, balanced parallel plate lines have been used.

The configuration of the line with its terminations is shown in Fig. 6. The characteristic impedance of the line was chosen as  $164 \Omega$ , the separation of the plates being made large enough for the meter under test to be placed between the conductors without altering the line impedance by an appreciable amount. The line was terminated by a  $\lambda/2$  line balun which fed a directional coupler and load with a matching

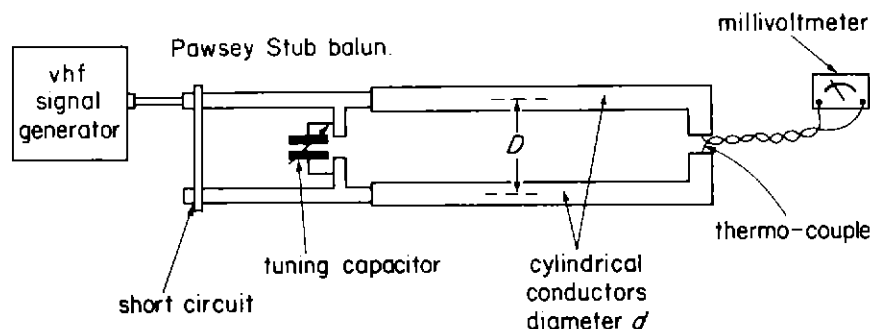


Fig. 5 - Arrangement of the transmission line for the absolute calibration of the ME1/4 meter at VHF.

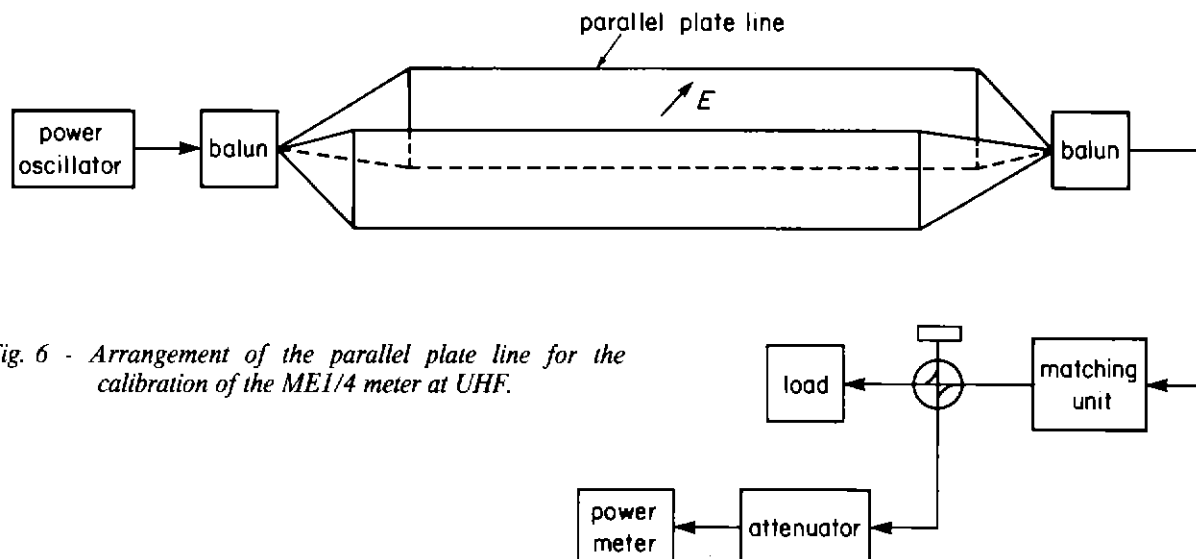


Fig. 6 - Arrangement of the parallel plate line for the calibration of the ME1/4 meter at UHF.

unit. The input to the line was fed from a generator through a  $\lambda/2$  line balun.

The calibrations were necessarily carried out at discrete frequencies as the method of matching was narrow band. A perfect impedance match was not entirely necessary because any residual standing waves could be detected by moving the meter along the line, and an allowance for it made in the calibration process. Of course, large standing wave ratios would lead to inaccuracy in the final results and it was important that values of VSWR were better than 0.9:1 at the calibration frequency.

### 5.1.3 Waveguide

A partial calibration check was made in the mid 1970s using a rectangular waveguide having a cross-section dimension of 0.610 m by 0.305 m. The guide was excited and terminated by monopole elements inserted in its broad side wall with the intention of generating the  $TE_{10}$  mode field distribution. A narrow slot was also cut along the centre of this side so that the standing wave ratio could be measured using a sliding probe.

The ME1/4 meter probe unit was inserted through a transverse slot cut in the narrow side wall of the guide and the calibration performed with only the probe unit inserted into the guide volume. From earlier tests, it had been seen that the presence of the whole meter within the guide space gave rise to sizable reflections which had led to uncertainty in the value of the electric field in the region of the meter itself.

The results obtained by this method gave reasonably good agreement with the original calibration over the limited operational frequency range of the

guide, i.e. between the cut-off frequency of the  $TE_{10}$  mode (250 MHz) and the onset of the  $TE_{11}$  and  $TM_{11}$  modes at 550 MHz. Above this range of frequencies the higher modes generated by imperfections in the guide structure cause increasing field strength variations. Ideally, a smaller dimensioned guide was required for calibrations at Band V frequencies, i.e. between 600 and 860 MHz. However, even at Band IV frequencies the arrangement was difficult to set up and the guide occupied considerable space in the laboratory. As a consequence, the method was not extended to the upper part of the UHF band.

### 5.1.4 Calibration at NPL

Recently the sub-standard meter has been calibrated by the National Physical Laboratory (NPL). They used a TEM cell at frequencies of 200 MHz and below, and a parallel line consisting of half-plane hyperbolic conductors at 300 MHz and above.

The first results showed that the meter read low at the top end of the UHF band. The meter was modified to correct its response and then re-calibrated at NPL.

To allow the modifications to be carried out, two different techniques were used. These are described next in Sections 5.1.5 and 5.1.6.

### 5.1.5 Horn

Further checks were carried out at the top of the UHF band where there was some disagreement between the original and subsequent calibrations. Here, a horn radiator was used and the field determined by measurement of the power coupled into a  $\lambda/2$  dipole when substituted in place of the meter under test in front of the horn.

### 5.1.6 Parallel plate line

A check calibration was made. A screened parallel plate line was used, of characteristic impedance equal to 100  $\Omega$ . Each conductor was terminated in a separate 50  $\Omega$  unbalanced load.

### 5.2 Results of calibrations

The results of the original calibration of the ME1/4 at NPL are shown in Fig. 7. It is clear that there is an inaccuracy in the original BBC calibration. Unfortunately there is, now, little information available to identify the cause of the problem.

A comparison of the different calibrations of the modified meter is shown in Fig. 8.

It can be seen that the results show there is a fairly close agreement between the different techniques. The NPL calibration accuracy is stated to be within 1 dB of the correct value. The accuracy of the other measurements is of course no better than that offered by the NPL.

As a matter of policy the results from the NPL are taken as the definitive calibration for all future work.

### 5.3 HF calibration

The method of calibration at HF has to provide a larger space of known field strength, and therefore higher absolute powers are needed (even though the field strengths are similar). Two methods of calibration have been employed: parallel plates, and a TEM cell.

#### 5.3.1 Parallel plates

Calibration was performed using tuned parallel metal plates as shown in Fig. 9. The plates were 0.5 m square and spaced 0.5 m apart and were tuned to resonance by the addition of input inductors. The Q of the arrangement was high enough for field strength values of greater than 1000 V/m to be obtained using transmitter powers of less than 20 W.

The voltage developed between the plates was measured using a valve voltmeter in conjunction with a capacitive potentiometer connected across the plates; in later calibrations the valve voltmeter was dispensed with and a current-loop probe, sampling the current in the capacitor chain, fed a power meter instead. In this case, a correction was needed for the conductor inductance which modifies the current level at the high-frequency end of the band.

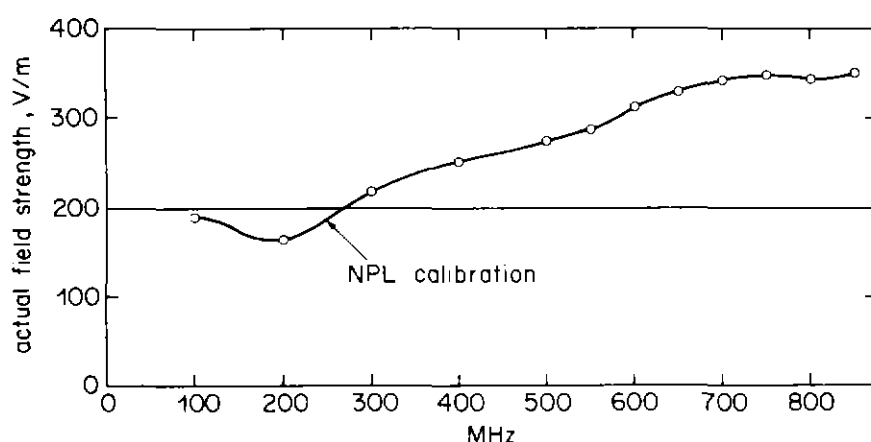


Fig. 7 - Results of first calibration of ME1/4 meter showing the error at the top end of the UHF band.

The curve shows the actual field strength required to give 200 V/m on the meter.

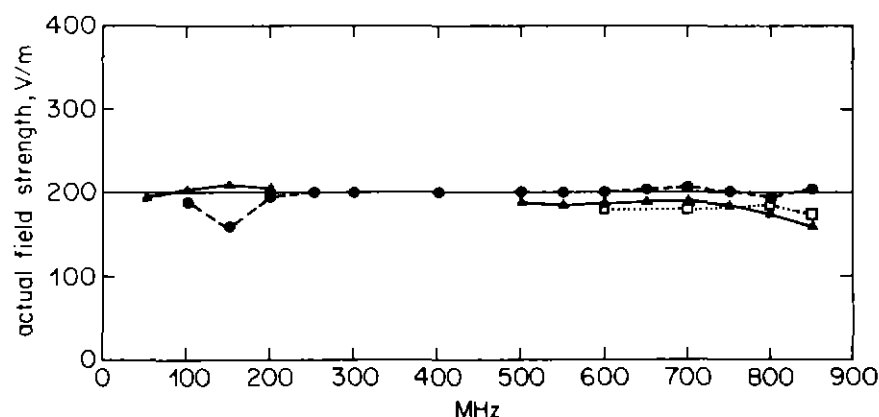


Fig. 8 - Actual field strength required to give 200 V/m on ME1/4 meter.

●---● NPL calibration  
▲---▲ Screened parallel plate line  
□---□ Horn

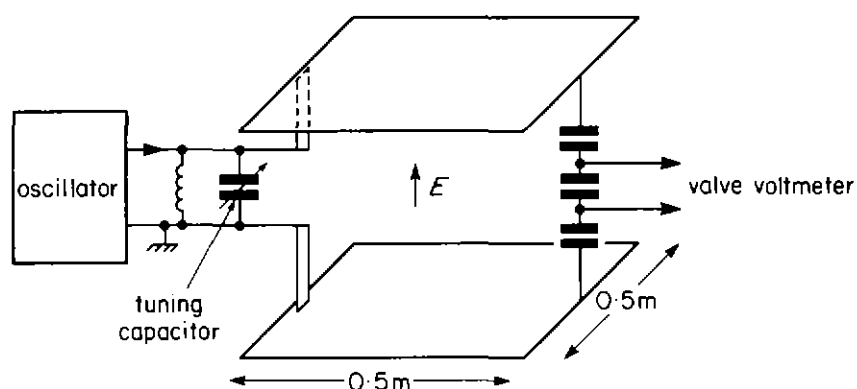


Fig. 9 - Calibration arrangement for HF field strength meter ME1/2.

### 5.3.2 TEM cell

The most recent re-calibration, in which the maximum scale reading was changed to 400 V/m, has been performed using a TEM cell driven from a 200 W linear amplifier.

Difficulties arise with the TEM cell measurements when the nominally linear amplifier produces harmonic distortion in its output. The response of the field strength meter and the monitoring power meter to the presence of the harmonic are different, e.g. a harmonic -20 dB relative to the fundamental level will change the field-strength meter reading by up to  $\pm 10\%$  while the monitoring power meter will change by only  $\pm 1\%$  (see also Section 7.2). It has been necessary to incorporate tuned filters into the output of the amplifier as shown in Fig. 10.

### 5.3.3 NPL calibration

This meter was also sent for definitive calibration at NPL. The NPL used a Crawford or NPL pyramidal TEM transmission cell to generate a known field for calibration.

The estimated uncertainty quoted by the NPL for the calibration was  $\pm 1.5$  dB. The BBC calibrations

were between 1.1 and 1.8 dB higher (i.e. on the safe side) than the results from the NPL.

## 6. CALIBRATION OF SERVICE METERS

The methods of calibration described in the previous sections were applied to the sub-standard meters. The work involved in using these methods is too prolonged for use with the service meters and a system of calibration by substitution is generally used.

In the case of the HF field strength meter the comparison can be performed directly by placing the sub-standard meter and the meter to be calibrated in the upper and lower septums of a TEM cell respectively. Provided that the meters are centred at the mid-height and the same lateral position in each septum, they can be compared directly. As this is a comparison, the absolute field strength need not be accurately known. The TEM cell can therefore be used as an unterminated line. This requires lower generator power to produce the wanted field strength and at the same time gives lower relative levels of harmonics than when full power is required from the generator.

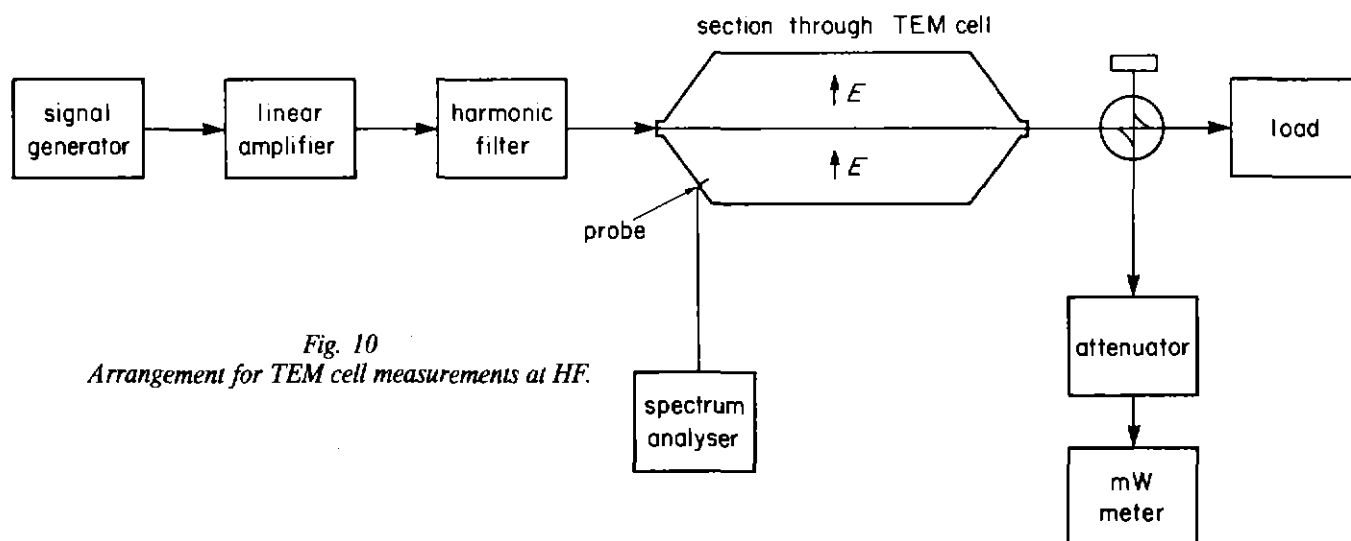


Fig. 10  
Arrangement for TEM cell measurements at HF.

The ME1/4 meter is calibrated using a substitution method. The sub-standard meter is inserted between the plates of a parallel-plate capacitor. The signal applied to the capacitor is then adjusted to the test frequency and the power increased to the point at which the meter reads the level at which the calibration is being performed. The sub-standard meter is then replaced by the meter to be calibrated. The scale reading for the meter under test should, when correctly aligned, be the same as that for the sub-standard meter. When the meter under test cannot be aligned exactly, it is aligned to read high (i.e. on the safe side). The target tolerance is 5%.

## 7. ACCURACY OF CALIBRATION

It is important to recognise that any physical measurement is subject to potential inaccuracies. For a meter used as a safety device it is desirable to understand these and make the appropriate allowances. Some of the problems can be calibrated out, whereas others will lead to residual errors.

In the case of the field strength meters there are two main sources of error. The first is the calibration process itself. The second is the fact that whereas the meters are calibrated for field strength using a single unmodulated carrier, it may be desirable to use them to identify power flow in an environment where there are multiple modulated carriers.

### 7.1 Problems of calibration

In the case of the transmission line used in Section 5.1.1 the electric field strength between the cylindrical conductors varies non-uniformly across the space between the conductors. Unless the conductors are sufficiently far apart, it is necessary to make corrections for these variations in field distribution. This is more complicated when the probes have a width which means that the field varies across the device. Although widening the conductor spacing reduces this variation, more power is required to produce the wanted field strength and greater uncertainty is introduced by increased radiation from the line.

The electric field intensity at the centre of a line with parallel cylindrical conductors is given by:

$$E_0 = 2V/(D \log_e (2D/d))$$

where  $V$  is the voltage between the conductors,  $D$  the spacing between and  $d$  the diameter of the conductors respectively.

The field distribution between the conductors is given by:

$$E_x = E_0/(1-(2x/D)^2).$$

This distribution is shown in Fig. 11. The correction factor for the effective field intensity using short dipole probe elements can be derived from the integral below:

$$E_{ef} = 2E_0 \int_0^L (1-y/L)/(1-(2y/L)^2) dy$$

where  $L$  is the half length of the dipole element. This becomes:

$$E_{ef}/E_0 = k(\log_e(k+1)/(k-1)) + k^2(\log_e(k^2-1)/k^2)$$

where  $k = d/2L$

Similarly the field distributions between the plates of both the screened and unscreened parallel plate lines are non-uniform, although, as might be expected, not to such a large extent as that between conductors of a balanced cylindrical conductor line. It is more difficult to predict the distribution in these cases. For the screened balanced plate line the solution can be found by using numerical techniques. The distribution obtained while using an over relaxation method<sup>2</sup> is shown in Fig. 12.

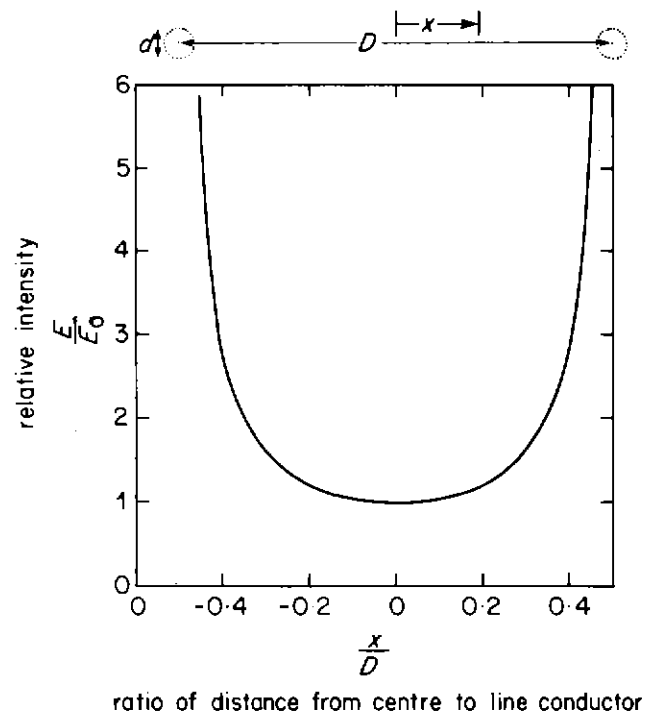


Fig. 11 - Variation of electric field strength intensity between parallel cylindrical conductors.

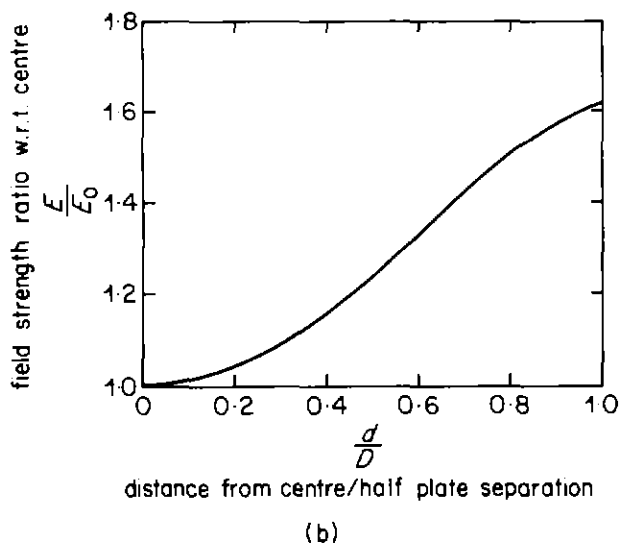
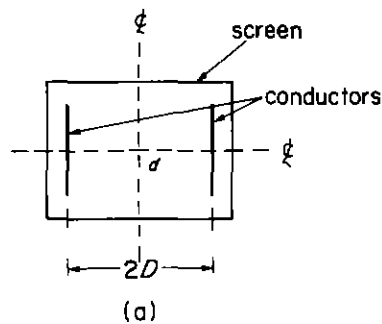


Fig. 12 - Variation of field strength intensity within a screened parallel-plate transmission line.

(a) Identification of symbols (b) Graphical relationship.

## 7.2 Problems of multiple or modulated carriers

The calibrations described in the previous sections have been performed using single, unmodulated carriers. In practice the field to be measured is often caused by multiple or modulated carriers.

The meters used in this Report detect the RF field strength, and then low-pass filter the resulting signal before it is applied to the meter. The time constants of the filters are long compared with the period of normal video or audio waveforms. Under these conditions the meter indicates the mean of the voltage envelope of the signal. The peak field strength will, under full modulation, be higher than that indicated on the meter. The power flux density will also be higher than that derived from the indicated field strength assuming CW operation.

The ME1/2 is used at HF stations which use amplitude modulation. The maximum error that may occur is when 100% amplitude modulation is applied. The peak field strength is twice that indicated and an error of up to 1.76 dB underestimate of the power radiated may occur. Of course, the average modulation

levels are more likely to be at the 30% level rather than 100% so that the average error becomes 0.2 dB.

At VHF, the ME1/4 will be presented with VHF-FM signals which are of constant envelope. In the presence of single carriers there should be no error in the reading.

At UHF, the ME1/4 is presented with 625-line television waveforms. The meter will give a deflection which corresponds to the correct average power density when the black level is being radiated. The assumed power density derived from the readings when white level is radiated (and no chrominance signal) will be approximately 4 dB low. The correction for average picture content will lie between these two levels.

The correction which may be required when multiple carriers are involved<sup>3</sup>, is a complex subject. It applies particularly to multiple transmissions from a common antenna where the fields near the antenna will consist of equal contributions from each of the transmissions. The response of the meters to the resulting waveform of the combined transmissions, will depend on the frequency ratios of the carriers and the RF time constants of the meters. For a peak detector, the maximum overestimate of power flow from field strength is  $10 \log_{10}(n)$  dB, where  $n$  is the number of programmes.

## 7.3 Near-field measurements

The dipole probes on the meters provide an accurate representation of the field in the far-field region of the antenna. In the near-field of the antenna, the probe measures not only the radiated components of the electric field, but also the reactive components.

The presence of reactive components complicates the issue. Mutual coupling between the probe and the antenna or mast structure can cause variations in the meter readings which do not reflect the unperturbed environment. This is a complex problem and is still under study.

## 8. CONCLUSIONS AND RECOMMENDATION

This Report has described the two meters currently made and used by the BBC for measuring RF field strengths. The two meters, the ME1/2 and the ME1/4 are rugged and simple to use.

The Report has detailed the techniques used to ensure that the meters are accurately calibrated. The calibration carried out within the BBC has been

backed up by independent calibration at the National Physical Laboratory.

The meters, in common with many others, are accurate for single frequency, continuous waves in the far-field of an antenna. The likely differences between the measured readings and the actual field strengths in a typical operational environment are discussed. It is noted that there is an uncertainty introduced into the measurement. In most instances inaccuracies cause the meter to register higher effective field strengths, i.e. providing a greater margin of safety.

Further work is required to develop improved methods of measurement of the potential for hazard of RF radiation in the near-field of a radiating antenna. Current methods may unnecessarily restrict broadcasting transmitter operations because of the need to

employ greater safety margins to account for the uncertainties inherent with available techniques.

## 9. REFERENCES

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